PATENT APPLICATION

WIDE-BANDWIDTH COAXIAL PROBE

CROSS-REFERENCE TO RELATED APPLICATIONS

This application is a continuation-in-part application of U.S. Patent Application Serial No. 09/738,044, entitled "Automated Domain Reflectometry Testing System", to Brian D. Butler, filed on December 15, 2000, and the specification thereof is incorporated herein by reference.

This application claims the benefit of the filing of U.S. Provisional Patent Application Serial No. 60/203,501, entitled "Wide-Bandwidth Coaxial Probe for Automated Testing of Planar Transmission Line Structures", to Brian D. Butler and Stephen M. Tobin, filed on May 11, 2000, and the specification thereof is incorporated herein by reference.

BACKGROUND OF THE INVENTION

Field of the Invention (Technical Field):

The present invention relates to probes for time domain reflectometry testing of electrical components.

Background Art:

Note that the following discussion refers to a number of publications by author(s) and year of publication, and that due to recent publication dates certain publications are not to be considered as prior art vis-a-vis the present invention. Discussion of such publications herein is given for more complete background and is not to be construed as an admission that such publications are prior art for patentability determination purposes.

The complexity of electronic components, particularly printed circuit boards, is steadily increasing, as is the demand for electronic components. These components need to be tested for faults, and high

frequency test techniques such as time domain reflectometry provides one technique for much of such testing. Because of the high volume of needed testing, automated robotic systems are preferred in order to attain a high throughput for any testing system.

Time domain reflectometry (TDR) is a technique for detecting impedance mismatches and other characteristics of microwave transmission lines. A very fast (order 50 ps) rising edge is injected, via electric probe onto the line, and line characteristics such as characteristic impedance and propagation delay are calculated from the step response recorded on a digital storage oscilloscope (DSO). With the advent of fast bus structures in computer memory applications such as RAMBUS, traces on printed circuit boards (PCBs) must now be treated as distributed circuits or transmission lines. As a result, computer memory and backplane manufacturers are now being asked by memory bus and integrated circuit designers to control the characteristic impedance of PCB traces.

Unfortunately, existing time domain reflectometry robotic testing systems suffer from noise introduced by certain sources of imprecision in the systems themselves. For example, U.S. Patent No. 5,994,909, to Lucas et al., discloses a robotic testing system having two probes 122,123 mounted on a single robotic arm wherein probe 123 is adjustable so that the distance between the two probes is adjustable. Such a mechanical system is prone to imprecision over time, because of vibration, temperature fluctuations, and like sources of distortion. Similarly, European Patent Application EP 0 953 844 A2 (corresponding to U.S. Patent No. 6,051,978, to Swart) discloses a two-probe system but having a single probe on each of two robotic arms. Again, maintaining a precise desired distance between the two probes is difficult, again resulting is unwanted distortion of the testing results. Because of such imprecisions in existing systems, the shortest traces that can be tested accurately are those that are 1.5 inches or longer.

The present invention greatly increases precision in domain reflectometry systems by employing twin probes (signal and ground) having a fixed distance (pitch) between them and having certain other desirable electrical characteristics. Because testing often requires a number of different pitches, a

robotic arm employing the invention is preferably able to select any of a plurality of fixed-pitch probes stored in a probe tip changer assembly, as disclosed in U.S. Patent Application Serial No. 09/738,044. Because this prevents inaccuracies induced by changes in pitch over time plaguing prior art mechanical systems, the present invention is able to successfully test traces as short as 0.5 inches. The shapes of the probe tips and the preferred rectangular shape of the probe tip assembly preserve accuracy by precisely matching the electrical characteristics of circular coaxial structures such as coaxial cables. The present invention has a number of other advantages over the prior art as discussed below.

U.S. Patent No. 4,740,746, to Pollock et al., discloses a controlled impedance microcircuit probe with a resilient center electrode in which impedance control is provide by maintaining a constant thickness of a dielectric between the center and the outer probe. The present invention does not have such limitation because air is used as a dielectric medium. Pollock et al.'s probe is also disadvantageous in that the compliance of the center electrode, provided by a multi-turn coiled spring, adds inductance to the ground circuit, thereby slowing the response time of the probe.

The following references disclose other electronic device probes having varying advantages and disadvantages: U.S. Patent No. 5,959,460, to Johnson; U.S. Patent No. 5,565,788, to Burr et al.; U.S. Patent No. 5,506,515, to Godshalk et al.; U.S. Patent No. 5,477,159, to Hamling; U.S. Patent No. 4,829,242, to Carey et al.; U.S. Patent No. 4,743,839, to Rush; U.S. Patent No. 4,686,463, to Logan; U.S. Patent No. 4,593,243, to Lao et al.; U.S. Patent No. 4,116,523, to Coberly et al.; and U.S. Patent No. 4,055,805, to Ardezzone. The following references disclose robotic testing systems having varying advantages and disadvantages: U.S. Patent No. 6,008,636, to Miller et al.; U.S. Patent No. 5,781,021, to Ilani; U.S. Patent No. 5,498,965, to Mellitz; U.S. Patent No. 6,024,526, to Slocum et al.; U.S. Patent No. 5,844,412, to Norton; U.S. Patent No. 5,696,450, to Itoh; U.S. Patent No. 5,498,964, to Kerschner et al.; U.S. Patent No. 5,469,064, to Kerschner et al.; U.S. Patent No. 5,105,147, to Karasikov et al.; U.S. Patent No. 4,881,863, to Braginsky; U.S. Patent No. 5,631,856, to Keller et al.; U.S. Patent No. 5,394,348, to Abe; U.S. Patent No. 5,043,910, to Chiba; U.S. Patent No. 4,628,464, to McConnell; and 4,593,820, to Antonie et al.

SUMMARY OF THE INVENTION (DISCLOSURE OF THE INVENTION)

The present invention is of a coaxial probe for testing of planar electric transmission line structures comprising: a probe mount comprising a coaxial connector; a center electrode mounted on the probe mount and electrically connected to a center conductor of the coaxial connector, wherein the center conductor may be placed in contact with a first point on a planar electric transmission line structure to be tested; an outer electrode mounted on the probe mount and electrically connected to ground, the outer electrode comprising a protrusion to be placed in contact with a second point on the planar electric transmission line structure to be tested; and a dielectric of non-uniform thickness between the center and the outer electrodes. In the preferred embodiment, the probe mount comprises a conductive plate and the dielectric comprises air. If the probe mount comprises a printed circuit board, the dielectric comprises the printed circuit board and air, and the printed circuit board may comprise one or more stubs for tuning electrical characteristics of the probe, and one or more shorting bars located along the one or more stubs. The outer electrode preferably comprises a conductive tube having a non-circular cross-section, such as oval, square, rectangular, hexagonal, L-shaped, or U-shaped. The protrusion may be placed at any point on a downward-facing surface of the outer electrode without substantially altering impedance characteristics of the probe. The pitch between the center electrode and the protrusion is preferably fixed. The protrusion preferably comprises a 60-degree point. The outer electrode may be axially spring-loaded to provide compliance. The connector may be spring-loaded to provide compliance, preferably via a short-throw conductive spring. The probe can be constructed to be handheld during testing of the planar electric transmission line structure. Impedance characteristics of the probe substantially match those of a coaxial cable attached to the connector. Lumped series resistance (such as a resistor) may be attached to the outer electrode to increase speed of the probe.

The invention is also of a differential coaxial probe assembly comprising two probes as described in the preceding paragraph.

The invention is additionally of a coaxial probe for testing of planar electric transmission line structures comprising: a probe mount; a center electrode mounted on the probe mount, wherein the center conductor may be placed in contact with a first point on a planar electric transmission line structure to be tested; and an outer electrode of non-circular cross-section mounted on the probe mount. In the preferred embodiment, the outer electrode comprises a protrusion to be placed in contact with a second point on the planar electric transmission line structure to be tested. The protrusion may be placed at any point on a downward-facing surface of the outer electrode without substantially altering impedance characteristics of the probe.

The invention is also of a differential coaxial probe assembly comprising two probes as described in the preceding paragraph, with fixed relative positions, with manually variable relative positions, or with automatically variable relative positions, and with either zero or one protrusion on a downward facing surface of each of the outer electrodes.

The invention is yet further of a coupled line differential probe assembly comprising: a probe mount; two center electrodes mounted on the probe mount, wherein both of the center conductors may simultaneously be placed in contact with first and second points on a planar electric transmission line structure to be tested; and an outer electrode of non-circular cross-section mounted on the probe mount, the outer electrode comprising zero, one, or two protrusions to be placed in contact with additional points on the planar electric transmission line structure to be tested. In the preferred embodiment, the protrusions may be placed at any point on a downward-facing surface of the outer electrode without substantially altering impedance characteristics of the probe. The outer electrode can comprise one protrusion to be placed in contact with a third point on the planar electric transmission line structure to be tested, or zero protrusions whereby a common ground is not provided between said outer electrode and the planar electric transmission line structure to be tested.

Objects, advantages and novel features, and further scope of applicability of the present invention will be set forth in part in the detailed description to follow, taken in conjunction with the accompanying

drawings, and in part will become apparent to those skilled in the art upon examination of the following, or may be learned by practice of the invention. The objects and advantages of the invention may be realized and attained by means of the instrumentalities and combinations particularly pointed out in the appended claims.

BRIEF DESCRIPTION OF THE DRAWINGS

The accompanying drawings, which are incorporated into and form a part of the specification, illustrate several embodiments of the present invention and, together with the description, serve to explain the principles of the invention. The drawings are only for the purpose of illustrating a preferred embodiment of the invention and are not to be construed as limiting the invention. In the drawings:

Fig. 1 is a perspective view of the probe of a robotic arm and tool changer assembly onto which the probe of the invention is mounted in one embodiment;

Fig. 2 is an exploded view of the probe of the invention, comprising a probe tip assembly and a ground electrode assembly, and showing a tool changer assembly attached to the probe of the invention via rigid shafts and sliding bushings;

Fig. 3 is an exploded view of the preferred probe assembly of the invention, wherein a center conductor of an SMA jack forms the signal electrode;

Figs. 4(a)-(e) are side and perspective views of the preferred signal electrode assembly of the present invention, and side, front, and top views of the preferred signal electrode tip of the present invention;

Figs. 5(a)-(d) are perspective, top, and two cross-section views of the preferred ground electrode assembly of the present invention used in conjunction with the signal probe assembly of Figs. 4(a)-(d);

Fig. 6 shows an embodiment with an axially spring-loaded outer conductor for compliance;

Fig. 7 shows an embodiment with an axially spring-loaded SMA jack for compliance;

Fig. 8 shows an embodiment with three nested outer conductors to extend the pitch of the probe;

Fig. 9 shows a double-stub tunable coaxial probe assembly according to the invention;

Fig. 10 shows an outer electrode assembly employing a lumped series resistance to improve step response time;

Fig. 11 illustrates an embodiment of a differential coaxial probe assembly with fixed probe-to-probe spacing;

Fig. 12 shows a coupled line differential probe of the invention; and

Fig. 13 illustrates a handheld probe assembly of the invention.

DESCRIPTION OF THE PREFERRED EMBODIMENTS
(BEST MODES FOR CARRYING OUT THE INVENTION)

The present invention is of an improved probe for time domain reflectometry testing of planar transmission line structures. A mount, such as a conductive plate (employing air as a dielectric) or printed circuit board (employing the PCB as the dielectric), is used to mount the probe structure. A miniature microwave connector jack (typically SMA or 3.5 mm) is attached to the probe mount and is used as the interface to a piece of coaxial cable leading to a digital storage oscilloscope (DSO) or other test control/monitoring device. On the opposite side of the probe mount from the connector jack, two electrodes (or more) are attached to the probe mount in a coaxial arrangement. The center electrode is preferably a round, solid metal pin of high electrical conductivity (e.g., gold-plated brass, gold-plated

beryllium copper, or gold-plated phosphor bronze). The outer electrode is preferably a metal tube, which is preferably oval, square, rectangular, hexagonal, L-shaped, or U-shaped of high electrical conductivity (e.g., gold-plated brass). Other configurations, including circular, are possible. A small protrusion is formed (e.g., machined, clipped, soldered, or otherwise attached) onto the outer electrode such that the distance from the center of the center conductor to the center of the protrusion is equal to the pitch of the PCB features to be probed.

The electrode dimensions are arranged so as to match the characteristic impedance of the cable, connector jack and connector jack-to-mount interface located in and on the opposite side of the probe mount. Such an impedance match is essential for optimum functioning of the invention. One of ordinary skill in the art can, for any desired combination of electrode materials, outer electrode shape, pitch between center and outer electrodes, etc., configure a probe according to the invention that will have such an impedance match. Most preferably, the outer electrode is configured such that the ground protrusion (nib) may be placed at any point on the downward facing surface of the electrode without affecting the impedance characteristics of the probe. The length of the protrusion is sufficiently short (<1/10 of the equivalent signal wavelength) such that any tip-to-ground impedance mismatch will not appreciably affect measurement precision.

The probe components are preferably mounted to a conductive metal plate that provides rigidity. The plate can also provide the weight (force) required for necessary electrical contact between probe tip ends and PCB features to be probed. The metal plate preferably contains two or more linear ball bearings (or brass bushings or plastic bushings) for ease of axial movement when mounted as the end tool of a robotic work cell. The metal block can be connected to an earth ground (such as being common with the case of the connector) to provide isolation from outside electrical interference.

Fig. 1 illustrates the robotic arm **10** onto which the preferred probe would be mounted. Robotic arm 10 may move in degrees of freedom as indicated by arrows **40**, in addition to independent placement in the x-y plane. A plurality of probe changer assemblies **20** may be engaged to and

disengaged from robotic arm **10** repeatedly as required. Mounted permanently to tool changer assembly **20** are two or more rigid shafts **30**, onto which the preferred probe would be installed and permitted to slide by means of low-friction bushings. Fig. 2 illustrates the preferred probe of the invention, comprising signal probe tip assembly **100**, conductive ground electrode assembly **110**, probe bracket **400**, sliding non-conductive bushings **212**, mounting collars **50**, and tool changer assembly **20** attached to the probe via compression springs **35** and rigid shafts **30**.

The components of the preferred probe tip assemblies of the invention are shown in Figs. 3, 4(a)-(e), and 5(a)-(d) which show the preferred but illustrative dimensions. Fig. 3 shows the components of the probe tip assembly which is comprised of the following: signal probe tip assembly **100** with two brass mounting screws **401**; ground probe tip assembly **110** (preferably made of brass) with two brass mounting screws **402**; probe assembly body bracket **400** (preferably made of brass); and two non-conductive bushings **212**.

Figs. 4(a) and (b) show the preferred signal probe tip assembly **100**, comprising a coaxial cable interface **109** which mates with a corresponding connector electrically connected back through the robotic arm to the testing instrumentation by coaxial cable and male/female connectors. The coaxial connector's ground is electrically connected to the ground flange **102**, and with the probe assembly body backet **400** through physical connection and through the two brass mounting screws **401** and thus with ground sleeve **110** through its mounting onto the probe assembly body bracket **400** with the two brass mounting screws **402**. The coaxial connector's signal is electrically connected with signal probe tip **104**, which is insulated from the ground flange **102**. The probe assembly body bracket **400**, has support holes which can be engaged by non-conductive bushings **212** to physically support the probe tip assembly. The preferred shape of signal probe tip **104** is shown in Figs. 4(c)-(e).

Turning now to Figs. 5(a)-(d), these show a rectangular conductive ground nib assembly **110**, which in use is physically connected with the probe assembly body bracket **400** such that base plate **116** is physically and electrically connected to probe assembly body bracket **400**, creating a conductive

ground path through sleeve **112** to ground nib/tip **114**. The dimensions of the assemblies **100** and **110** are arranged so that both nib **114** and signal probe tip **104** preferably protrude from sleeve **112** by the same distance. A 60-degree point is preferred for the ground nib. Alternatively, signal probe tip **104** can be longer in order to permit it to be compliant when contacting a board under test.

Assemblies **100** and **110** are configured so that by placing the nib **114** at any point on sleeve **112**, the electrical impedance of the combined assembly is such that a coaxial cable structure is sufficiently matched despite changes in distance (pitch) between nib **114** and signal probe tip **104**. Preferably, the conductive portions of the assemblies are composed of a copper-based alloy.

In order to overcome the difficulties inherent in making the signal and ground electrodes exactly the same length, as shown in Fig. 6, the outer electrode **510** can be configured as an axially spring-loaded conductor member in order to provide compliance. Alternatively, as shown in Fig. 7, the probe may be configured such that the entire connector assembly **520** is resilient rather than a single conductor. This results in movement of the signal electrode **521** instead of the ground electrode (not shown). Compliance is provided by having connector assembly **520** move along metal pins **522** in the upward direction as indicated by the arrow **535**, while contacting conductive washers **523** and conductive wave springs **524**. Movement is limited by conductive stops **525** attached to base bracket **530** by conductive mounting screws **526**. Short-throw wave washer type springs **524** are preferred in that these lessen the introduction of excess inductance into the system.

The pitch range of the probe can be extended by nesting one or more larger outer electrodes of tubular construction over the first outer electrode and attaching (e.g., soldering or otherwise adhering) the two electrodes together to form a firm electrical contact. If air space exists between the two electrodes, the air space can be filled with pieces of high-conductivity material of appropriate dimensions and attached (e.g., soldered or otherwise adhered) to the electrode assembly. As shown in Fig. 8, the center electrode **540** is surrounded by an inner tube **541**, intermediate tube **542** and outer electrode **543**, configured with ground nib **544** and mounting flanges **545**. Air spaces are filled by plate pairs **546**

and **547**. The impedance match previously described is preserved by retaining inner tube size and shape **541** as shown in Figs 5(a) to (d).

Fig. 9 illustrates a double-stub tuned passive coaxial probe assembly **580** for a more precise impedance matching of probe to SMA jack and cable, embodied by locating stubs **590** as traces **600** and pads **610** (holes) on both sides of the probe PCB mount **620**. Dashed traces **601** are indicated as being on the back side (bottom) of the PCB. Shorting bars **630** are soldered in place at specific locations along both of the stubs to provide the necessary tuning function. In this case SMA jack assembly **635** with an extended center electrode **636** is soldered into holes **637** within the PCB. Single-stub embodiments are also possible.

If it is desired to further improve probe speed, Fig. 10 shows a ground electrode assembly **640** comprising a lumped resistance in series with ground electrode **645**, such that the step response time of the probe is shortened. This can be implemented employing surface mount resistor **650** (e.g., 51 ohms) or other resistance means.

Fig. 11 illustrates a differential passive coaxial probe assembly **660** comprising two probe assemblies **670,671** mounted at a fixed spacing on the same mounting block **675**. In another embodiment, two probe assemblies are mounted on two slotted or otherwise moveable probe mounts and on the same mounting plate such that the probe mounts are manually movable to produce variable spacing of the probe assemblies. In another embodiment, the probe mounts comprise conductive gears which are automatically movable via an electric motor or other means to produce variable spacing of the probe assemblies. For these differential configurations, it is preferred to have the position of the ground nib on each assembly **690,691** mirrored with respect to each center conductor in order to balance axial test contact forces along the assembly center of mass.

Fig. 12 shows a coupled line differential probe **700** comprising a single probe assembly **710** with two separately excited signal conductors **713,714** and either one or two ground nibs **715,716** on the

outer conductor. In a variation of this embodiment, the outer conductor is void of ground nibs, such that the ground signal is not physically connected to the planar transmission line structure under test. In this arrangement, the transmission line under test is capacitively coupled to the nearest source of ground potential. This compact arrangement allows smaller pitches than those possible with the arrangement of Fig. 11. Impedance matches can be made for both odd (differential) and even (common) mode signal excitations.

Fig. 13 illustrates a handheld probe assembly **720** according to the invention.

Although the invention has been described in detail with particular reference to these preferred embodiments, other embodiments can achieve the same results. Variations and modifications of the present invention will be obvious to those skilled in the art and it is intended to cover in the appended claims all such modifications and equivalents. The entire disclosures of all references, applications, patents, and publications cited above are hereby incorporated by reference.